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EXECUTIVE SUMMARY

WATER INGRESS INTO POWER TRANSFORMERS

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A comprehensive study of water migration in power transformers was carried out using transport and thermodynamic equations. A mathematical model which describes moisture equilibrium distribution in a 750 MVA unit was developed. This model was subsequently used to calculate moisture equilibrium content in the insulating materials at different environmental conditions. It was established that moisture in the solid insulation (paper, pressboard and wood) and insulating materials degradation reactions are the most important sources of water in the unit. Although open to the atmosphere there is essentially no transfer of moisture between the oil in the unit and ambient. This is a direct consequence of the low diffusivity of water in insulating oil, the relative long diffusion path and the rather low moisture concentrations involved. Water condensation, a phenomenon commonly observed in in-service units is expected to occur in highly humid transformers continuously exposed to swings in temperature. Because of the impact that these findings may have in maintenance practices of power transformers, it is recommended that these should be confirmed by an experimental study.

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32-139-333	832.77	September 4, 1987	87-197-K

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To: Mr. G.E. Woolley
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WATER INGRESS INTO POWER TRANSFORMERS

Luciano A. Gonzalez

A comprehensive study of water migration in power transformers was carried out using transport and thermodynamic equations. Because of the low diffusivity of water in insulating oil, the relative long diffusion path and the moisture concentrations involved, although open to the atmosphere these units are essentially isolated from the ambient. The initial water in the paper and that originating from insulating degradation seem to be the most important source of water. Water condensation, a commonly observed phenomenon in field units, is expected to occur in highly humid transformers exposed to swings in temperatures.

1.0 INTRODUCTION

Moisture content in electrical transformers has been found to be an important factor in the deterioration of insulating materials. Increases in the moisture level of insulating paper result in an accelerated aging of the solid material while excessive water in the oil causes a reduction of the dielectric strength of the fluid mainly due to bubble formation and tracking.

It is the general understanding that moisture in power transformers comes from two well defined sources: the byproducts of the insulating materials degradation and migration of water vapour from the ambient into the unit. Small amounts of moisture left in the dielectric help to degrade the insulation and by chemical action more water is produced. Meanwhile moisture in the ambient air can diffuse into the transformer through the breathing system. Because it is believed that external moisture migrating into transformers is a significant fraction of the

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total water content in these units, different protective systems (ie. dryers) to prevent this diffusion process have been used/1/. Although the use of protective mechanisms in transformer breathers has been stressed in the utility industry, no attempt to evaluate their need or effectiveness has been made.

The objective of this project was to develop a mathematical model which could describe moisture equilibrium distribution in power transformers. This model could also be used to determine the rate of moisture ingress into the units and to evaluate the need for the use of protective mechanisms for transformer breathing systems. The mathematical model can be used by power transformer maintenance staff to determine the need for moisture control in oil preservation system for units in service in locations with different environmental conditions.

2.0 REFERENCE CONFIGURATIONS

A new 750 MVA power transformer with dry oil and insulating paper was the base for the development of the mathematical model. To simplify the mathematical complexity of the model it was assumed, as shown in Figure 1, that the power transformer consisted of a metal case enclosing 9,678 kg of insulating paper (paper, pressboard and wood) and filled with 147,900 kg of insulating oil. Two oil conservators of 8 m^3 capacity each were connected to the transformer body through a 6 m long, 5 cm diameter pipe/2/. It was also assumed that the oil in the transformer was well mixed, while the oil in the connecting pipes and conservators was stagnant. The oil in the pipes would move only as a solid piston due to expansion and contraction of the fluid caused by system temperature variations.

It is also assumed that the unit is fully loaded and at this condition the paper and insulating oil tempertures are 66 and 40 degrees above ambient respectively. The original insulating paper was assumed to have a moisture level of 5 mg H_2O/g paper, while the insulating oil is completely dry.

Since it was expected that ambient relative humidity and temperature would have an important effect on the migration and distribution of water in the transformer, data for two different locations, Ontario North and Ontario South which represent extreme conditions for the Province were considered in this study/3/.

3.0 MOISTURE INGRESS INTO TRANSFORMERS

Water migrates from the ambient into a transformer through the conservator. Moisture in the air is absorbed by the oil at the oil/air interface and diffuses into the transformer through the oil in the connecting pipe. The diffusing water is then taken up by the circulating oil in the transformer. Some of the water in

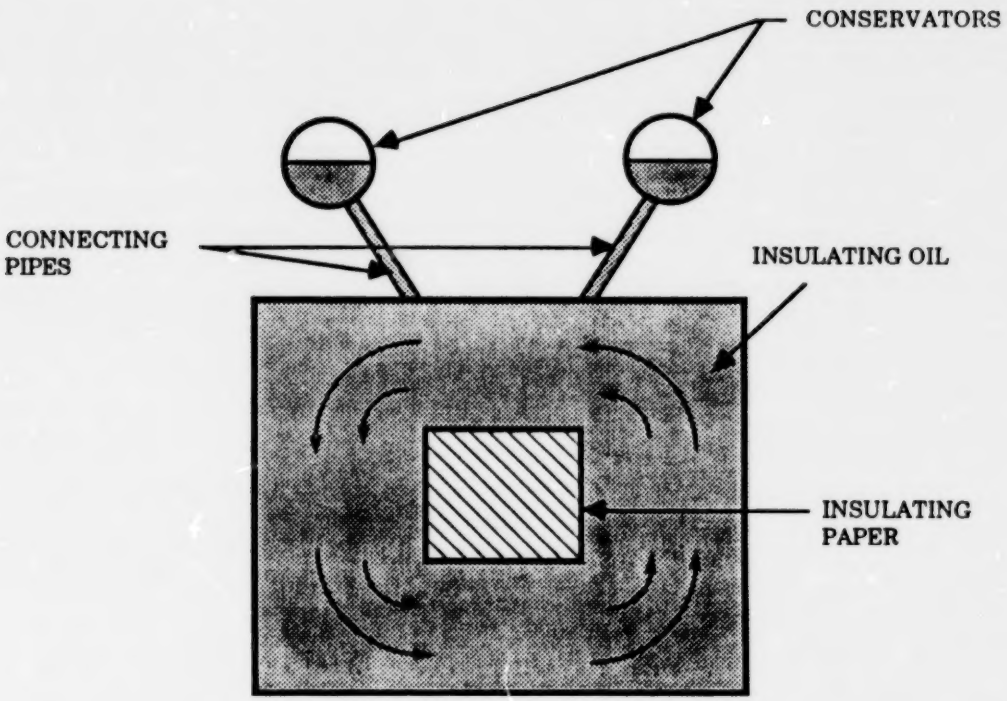

FIGURE 1

SCHEMATIC REPRESENTATION OF A 750 MVA POWER TRANSFORMER

the oil is transferred to the insulating paper. The migration process continues until the partial pressures of water in all phases are the same.

Besides the migration process of moisture from the ambient, water is also generated in the unit due to the thermal decomposition of the paper and other cellulose-based materials. The amount of moisture generated in the transformer would depend on the paper content in the unit and on the system temperature.

Since the equilibrium state depends on the unit's thermal conditions, variations in transformer electrical loading or ambient temperature will affect the water distribution. Because the unit is open to the ambient, relative humidity will also affect the moisture distribution in the transformer. The rate of water migration in the unit is governed by Fick's law of diffusion/4/, while the equilibrium distribution of moisture between the different phases in the transformer is determined by the moisture isotherms for the air-oil and oil-paper systems/5/. The rate of water generation from paper degradation was determined from literature data/6/.

3.1 Diffusion Equation

Application of Fick's law of diffusion/4/ allows one to calculate the rate of migration of a substance between two positions at different concentrations,

$$F_d = -D \frac{\partial C}{\partial x} \qquad (1)$$

where F_d is the rate of diffusion per unit area of section, ∂C is the differential concentration of the substance, ∂x the differential diffusing path and D the diffusivity of the substance in the medium. Applying equation 1 to the different sections in the unit, conservator, connecting duct and transformer and neglecting the interface resistances, the expression for the rate of moisture migration under steady state becomes,

$$N_w = \frac{C_s - C_i}{R_{ov}} \qquad (2)$$

where N_w is the water flow rate (moles s^{-1}), C_s and C_i are the water concentration in the oil at the oil/air interface and in the transformer in moles cm^{-3} and R_{ov} is the overall diffusion resistance given by:

$$R_{ov} = \frac{\ell_1}{D_1 A_1} + \frac{\ell_2}{D_2 A_2} + \frac{\ell_3}{D_3 A_3} \qquad (3)$$

with ℓ the diffusion path (cm), D the diffusivity ($cm^2 s^{-1}$), and A cross section area (cm^2), for the conservator 1, joint 2, and transformer 3 respectively. Under normal operating conditions the values for the transformer become negligible due to oil mixing.

Because of the temperature variations in the different sections of the unit, it is more appropriate to write equation 2 in terms of the water partial pressure. Thus,

$$N_w = \frac{(P_s/T_s - P_i/T_i)}{R\, R_{ov}} \qquad (4)$$

where p and T are the water partial pressure in atm and temperature in K, at the air/oil interface and transformer and R the universal gas constant (atm L K^{-1} $mole^{-1}$).

The diffusivity of a gas in a liquid medium is usually an exponential function of temperature and can be expressed by an Arrhenius-type relationship. For the water diffusivity in insulating oil this dependency has the form of/7/

$$D = 804.1 \exp(-5388/T) \qquad (5)$$

where D is in $cm^2 s^{-1}$ and T in Kelvin.

As indicated by equation 4 it is expected that the initial moisture content in the insulating paper, system temperature variations and ambient relative humidity would affect the rate of water migration in the unit.

3.2 Water Formation

It is known that water is produced as a byproduct in the thermal and chemical decomposition of insulating paper and other cellulose-based materials/6/. The degradation of cellulose is a complex process which depends on several factors such as temperature, rate of heating, oxygen and moisture concentration and type of paper. The rate of water formation due to paper thermal decomposition for Kraft insulating paper has been studied/6/. It was found that water is formed as a function of temperature according to

$$\log(m) = 17.3 - 8550/T \qquad (6)$$

where m is the rate of water formation in mg H_2O/h g paper and T is the absolute temperature. This equation was used here to

calculate the amount of water generated per unit time in the reference power transformer as a function of system temperature.

3.3 Moisture Equilibrium

Since insulating oil in a power transformer is in contact with ambient air through the breathing system and with the insulating paper, equilibrium distribution of water in the unit requires that the equilibrium state must be reached in both air-oil and oil-paper systems. The expression for the moisture distribution in an oil-air system was obtained using literature data/5/:

$$C_o = 2.76 \times 10^5 \exp(-3861.4/T_o) \quad RH \qquad (7)$$

where C_o is the moisture concentration in oil (mg H_2O/kg oil), T_o the oil absolute temperature, and RH the ambient relative humidity (%). Similar to the air-oil moisture equilibrium distribution, literature data were also used to derive an expression for moisture equilibrium in the oil-paper system/5/,

$$C_p = 1.525 \times 10^{-8} \exp(3780.8/T_p)\, C_o \qquad (8)$$

where C_p is the water concentration in the solid (gH_2O/g paper), T_p the paper absolute temperature, and C_o the concentration of moisture in insulating oil with the same units as in equation 7.

The simultaneous solution of equations 7 and 8 yields the distribution of water in the ambient air, insulating oil and paper under equilibrium conditions. The computer code TK! Solver (Software Arts, Inc. MA) was used to write a program for calculating this distribution in power transformers as a function of system temperature and ambient relative humidity. This program was run on a personal microcomputer (IBM PC) to obtain the rate of migration of water in transformers and moisture equilibrium distribution at different environmental and loading conditions.

4.0 EFFECTS OF ENVIRONMENTAL CONDITIONS

The effects of ambient relative humidity and temperature on the rates of water diffusion and formation in a power transformer located in Ontario North are summarized in Table 1. As observed in the table the diffusion rates of water migrating in the unit are extremely low. This is a direct consequence of the low diffusivity of water in the insulating oil and the low moisture concentrations involved. This low migration rate makes the transformer to be essentially isolated from the ambient. There is no significant exchange of water between the transformer and the ambient air.

Table 1

Water Diffusion and Formation Rates in a 750 MVA Power Transformer Located in Ontario North

Season	Relative Humidity	Ambient Temperature	Diffusion Rate	Formation Rate
	%	°C	$\frac{g}{year}$	$\frac{g}{year}$
Spring	65	0	-1.3×10^{-4}	1.0
Summer	71	15.4	4.2×10^{-3}	12.7
Fall	80	3.8	4.0×10^{-4}	1.9
Winter	78.3	-16.0	-3.1×10^{-4}	0.1

Note that the diffusion rates summarized in Table 1 were calculated neglecting all interfacial resistances and considering that the oil in the conservator was the only resistance to water diffusion in the system. The oil in the connecting pipe between the transformer and the conservator does not represent a significant resistance to diffusion when the unit is subject to constant swings in temperature. The variations in the system temperature caused by changing the electrical loading of the unit or by natural day and night temperature fluctuations cause the insulating oil in the transformer to expand or to contract. The small volume of oil in the connecting pipe is displaced as a piston, therefore eliminating this resistance to diffusion. For units under constant operating temperatures, the expansion and contraction phenomena of the fluid do not occur and the oil in the connecting pipe becomes the most significant resistance to moisture diffusion. The inclusion of this resistance results in a reduction of about 3 orders of magnitude of the moisture diffusion rate given in Table 1.

It is also observed in Table 1 that the direction of water diffusion can be reversed due to changes in the ambient conditions. Positive flows from the ambient into the unit are obtained at relatively high relative humidities and temperatures. Under these conditions the water partial pressure in the ambient air is higher than the moisture partial pressure in the transformer. A reduction in the water partial pressure caused by lower temperatures or relative humidities may reverse this gradient, resulting in water flowing from the transformer out to the ambient (negative diffusion rates in the table).

Since the transformer is essentially isolated from the ambient air and the rate of water formation in this unit is significantly greater than the rate of diffusion, water generated in the system will remain in the transformer. As water accumulates in the unit moisture in the insulating oil will approach saturation level. Drops in the system temperature may result in water condensation. A similar situation can be expected if the original moisture level in the insulating paper is relatively high. In this case significant amounts of water will be dissolved by the hot insulating fluid. Drops in the ambient temperature or loading conditions will reduce the water dissolving capacity of the oil resulting in a moisture saturated fluid. If the amount of water in the oil exceeds the moisture holding capacity of the fluid condensation and phase separation of the water will occur. Water condensation and settling at the bottom of the transformer is a phenomenon commonly observed in field units.

The equilibrium water distribution for the reference transformer was calculated as a function of the average climatic conditions for Ontario North. These values are summarized in Table 2. By comparing the value of the equilibrium moisture content of the paper shown in Table 2 to the initial value of 5 mg H_2O/g paper one can readily indicate if water is being gained or lost by the system.

Table 2

Equilibrium Distribution of Water
in a 750 MVA Power Transformer
Located in Ontario North

Season	Relative Humidity	Ambient Temperature	Paper Moisture Content	Oil Moisture Content
	%	°C	mg H_2O / g paper	mg H_2O / kg oil
Spring	65	0	3.9	3.7
Summer	71	15.4	6.5	10.0
Fall	80	3.8	5.4	5.9
Winter	78.3	-16.0	2.8	1.5

Similar to the data shown in Tables 1 and 2 for Ontario North, moisture diffusion, water formation rate and equilibrium distribution were calculated for Ontario South. These data are summarized in Tables 3 and 4.

Since higher temperatures are observed in the South than in the Northern region, the rate of water formation was found to be significantly greater under the warmer conditions. The rates of water formation are also higher than those indicated in Table 1 for the same reason. Because of the higher rate of water formation in transformers located in warmer areas, the rate of moisture accumulation will also be greater than those observed in colder climates.

Table 3

Water Diffusion and Formation Rates
In a 750 MVA Power Transformer
Located in Ontario South

Season	Relative Humidity	Ambient Temperature	Diffusion Rate	Formation Rate
	%	^{o}C	$\frac{g}{year}$	$\frac{g}{year}$
Spring	70	7.3	4.8×10^{-4}	3.4
Summer	66	20.7	1.0×10^{-2}	28.7
Fall	75	11.0	1.9×10^{-3}	6.3
Winter	80	-3.3	-1.7×10^{-5}	0.6

Table 4

Equilibrium Distribution of Water
in a 750 MVA Power Transformer
Located in Ontario South

Season	Relative Humidity	Ambient Temperature	Paper Moisture Content	Oil Moisture Content
	%	^{o}C	$\frac{mg\ H_2O}{g\ paper}$	$\frac{mg\ H_2O}{kg\ oil}$
Spring	70	7.3	5.2	6.2
Summer	66	20.7	6.9	12.4
Fall	75	11.0	6.2	8.2
Winter	80	-3.3	4.4	3.7

5.0 Effects of Initial Moisture Content

The effects of the initial moisture content in the insulating paper on the rate of migration and the direction of water flow in power transformers have also been determined. Table 5 summarizes the results obtained for a unit whose insulating paper has moisture levels in the range of 2.0 to 20.0 mg H_2O/g paper. These values were calculated for a tranformer at an ambient temperature of 3.8°C and a relative humidity of 80%. As expected an increase in the initial moisture content in the unit reduces the amount of water migrating into the transformer. Moreover, further increases (e.g. from 8 mg/g) in the original moisture content can reverse the water flow in the unit. Depending on the excess of water and thermal conditions, water condensation in the transformer may occur.

Since water flow in the unit depends on the moisture concentration gradient between the surface oil (in the conservator) and the transformer, high flow rates will be achieved as this concentration gradient increases (very low or very high initial moisture content). This is actually observed in Table 5 where the highest migration rates are obtained for very dry (2.0 mg/g) or very humid (20.0 mg/g) systems.

Table 5

Effects of Initial Moisture Content of Insulating Paper on Rate and Direction of Water Migration in Power Transformer

Initial Moisture In Paper	Water Diffusion Rate
(mg/g)	(g/y)
2.0	1.6×10^{-3}
5.0	4.0×10^{-4}
8.0	-7.6×10^{-4}
10.0	-1.5×10^{-3}
20.0	-5.4×10^{-3}

6.0 CONCLUSIONS

A comprehensive study of water migration in power transformers was carried out using transport and thermodynamic equations. The main conclusions drawn from this study are:

- Although the transformers are open to the atmosphere through the breather, the low diffusivity of water in insulating oil, the relatively long diffusion path and the low concentrations involved make this system essentially isolated from the ambient.

- Initial moisture content in the insulating paper and subsequent water generation from degradation of insulating materials are the most important sources of moisture in the transformer.

- Water condensation and therefore phase separation may take place in units with high moisture levels which are exposed to swings in temperature.

7.0 RECOMMENDATION

Because of the great impact that these findings may have on maintenance practices of power transformers it is recommended to carry out an experimental study. This study should have as objectives the validation of the model hereby presented, to confirm that insulating paper decomposition is an important source of water in these units and to evaluate the use of dryers as a controlling mechanism for moisture in power transformers.

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